

Project Portfolio: Solid State Lighting

U.S. Department of Energy Energy Efficiency and Renewable Energy Building Technologies Program

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Solid State Lighting Project Portfolio

The U.S. Department of Energy (DOE) partners with industry, universities, and national laboratories to accelerate improvements in solid state lighting (SSL) technology. These collaborative, cost-shared efforts focus on developing an energy-efficient, full spectrum, white light source for general illumination. DOE supports SSL research in six key areas: quantum efficiency, longevity, stability and control, packaging, infrastructure, and cost reduction.

The *Solid State Lighting Project Portfolio* provides an overview of SSL projects currently funded by DOE. Each profile includes a brief technical description as well as information about project partners, funding, and time frames. The Portfolio is a living document and will be updated periodically to include new projects that are initiated.

Table of Contents

LIGHT EMITTING DIODES

Building Technology/NETL

High Efficiency LED Lamp for Solid State Lighting	5
LED Package Efficiency and Brightness	6
LED Substrates and New Materials	8
Nanostructured High Performance Ultraviolet and Blue LEDs	10
Novel Approaches to High-Efficiency III-V Nitride Heterostructure Emitters for Next-Generation Lighting Applications	12
Phosphor-Free Solid State Light Sources	13

EE Science Initiative

Development of Photonic-Crystal LEDs for Solid State Lighting	15
Development of UV-LED Phosphor Coatings For High Efficiency Solid State Lighting	16
Innovative Development of Next-Generation and Energy-Efficient Solid State Light Sources for General Illumination	18
Novel LED Phosphor Research	20
Novel LED Structures	21

Small Business Innovation Research

Development of Silicon Nanocrystals as High Efficiency White Phosphors	22
Efficient Hybrid Phosphors for Blue Solid State LEDs	24
Enhanced Optical Efficiency Package Incorporating Nanotechnology Based Downconverter and High Refractive Index Encapsulant for AlInGaN High Flux White LED Lamp With High Luminous Efficiency LED Phosphor Performance (Phase 1)	25
Gallium Nitride Substrates for Improved Solid State Lighting	26
Novel Low-Cost Technology for Solid State Lighting	28
Ultraviolet LEDs for Solid State Lighting	29

ORGANIC LIGHT EMITTING DIODES

Building Technology/NETL

[OLED Durability and Performance](#)..... 31

[Polymer OLED White Light Development Program](#) 33

Small Business Innovation Research

[General Illumination Using Dye-Doped Polymer LEDs](#)..... 35

[New Solid State Lighting Materials \(Phase 1\)](#)..... 37

[New Solid State Lighting Materials \(Phase 2\)](#)..... 38

[New Stable Cathode Materials for OLEDs](#)..... 39

[Novel Light Extraction Enhancements for OLEDs](#)..... 41

[Novel Lower Voltage OLEDs for High Efficiency Lighting](#) 42

[Polymer White Light Emitting Devices](#)..... 44

[White Illumination Sources Using Striped Phosphorescent OLEDs](#) 46

[Monomer-Excimer Phosphorescent OLEDs for General Lighting](#)..... 46

[Novel High Performance OLED Sources \(Phase 2\)](#)..... 48

High Efficiency LED Lamp for Solid State Lighting

Investigating Organization

Cree Santa Barbara Technology Center

Principal Investigator

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Subcontractor

None

Funding Source

Building Technology/NETL

Award

DOE share: \$1.41 million; applicant share: \$473,194

Contract Period

October 2003 to October 2006

Research Topic

Topical Area 1: Applied Research Area

Task 1.2: Advanced Device Architectures & Conversion Materials

Subtask 1.2.1: Advanced Architectures for High-Power-Conversion Efficiency Emitters

Cree SBTC is working to develop technology that will enable high efficiency, cost-effective LED lamps for solid state lighting. The objective of the program is to demonstrate the potential for solid state lamps based on GaN semiconductor LEDs to be viable replacements for existing energy inefficient incandescent light sources in terms of efficiency and cost. Compared to white LEDs available today, the end product will be significantly higher efficacy LEDs operating at an order of magnitude lower cost performance measured in dollars per kiloLumen.

These goals will be achieved by combining innovative approaches in (a) GaN-based materials technology, (b) LED device fabrication, and (c) solid state lamp packaging. GaN-based materials and LED chip design will be optimized to enable very high current density operation of LEDs. Novel device designs will be developed to increase the photon extraction efficiency from LED devices. Packaging technology will be developed that allows an increase in power dissipation from a given footprint and makes more efficient use of the light emitted from the LED chips. Together, the improvements will deliver a lot more light per LED chip unit area, which is key to making possible substantial energy savings with solid state lighting in the near future

LED Package Efficiency and Brightness

Investigating Organization

Cree

Principal Investigator

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Subcontractor

Lawrence Berkeley National Laboratory (LBNL)

Funding Source

Building Technology/NETL

Award

\$2,247,250

Contract Period

September 2000 to July 2004

Research Topic:

Research Topical Area 1: Applied Research Area

Task 1.2: Advanced Inorganic Device Architectures & Conversion Materials

Subtask 1.2.1: Advanced Architectures for High-Power-Conversion Efficiency Emitters

Cree and LBNL are pursuing high-efficiency, high-radiance LED and packaging technology that will push LED brightness into the 60-100+ lumens/watt range. At such levels, novel solid state lamps using a few LED "filaments" should be capable of replacing less energy-efficient lighting technologies. Potential benefits include lamp dimability, efficiency, consistent lifelong color, extended lamp life, and the absence of toxic materials.

To date, Cree has demonstrated >40 lumens at 35 lumens per watt using a single LED, and a compact lamp prototype with an output of >1,000 lumens at over 30 lumens per watt using multiple LEDs. The latter lamp provides roughly the same amount of light overall as a commercial halogen reflector lamp but at twice the energy efficiency.

In this research, Cree is leveraging its highly efficient Gallium Indium Nitride on Silicon Carbide (GaInN/SiC) emitter technology that demonstrates efficient chip-level thermal management techniques. Advanced chip designs and fabrication techniques are being developed to increase the energy efficiency of the LED chip by reducing the optical and electrical losses that typically occur. The development process uses a combination of optical modeling, device simulation, fabrication, and characterization of device prototypes to assess the impact of various design modifications on chip performance.

In addition, novel solid state lamp package technology is being developed with LBNL to ensure that light emitted from the LED chip can be used efficiently in actual lighting applications. This

work includes thermal and optical modeling to establish package design constraints, use of high-performance materials, and development of working prototypes to see how various materials and design geometries affect heat dissipation and light output from a compact LED source.

LED Substrates and New Materials

Investigating Organization

Lumileds Lighting, U.S., LLC

Principal Investigator

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Subcontractors

Sandi National Laboratories (SNL)

Funding Source

Building Technology/NETL

Award

\$1,377,000

Contract Period

September 2001 to December 2003

Research Topic

Topical Area 1: Applied Research Area

Task 1.1: Inorganic Materials Research

Subtask 1.1.3: Reliability and Defect Materials Physics for Improved LED Lifetime

Lumileds Lighting is working with Sandia National Laboratories (SNL) to understand how and why certain physical and chemical processes affect the performance of selected compound semiconductor LEDs. The project has three research areas: (1) the study of performance impacts caused by different kinds of material dislocations and defects and ways to reduce these for Gallium Nitride (GaN) grown on sapphire substrates; (2) the direct measurement of various physical properties of different semiconductor layers during reactor growth in production tools; and (3) the feasibility of using semiconductor nanoparticles for the efficient conversion of blue or ultraviolet light to broad spectrum, high-quality, bright white light.

A cantilever epitaxy (CE) process developed at SNL has reduced dislocation density in GaN. CE is a simplified approach to low dislocation density GaN that requires only a single substrate etch before a single GaN growth sequence. CE has achieved low dislocation density GaN in layers only a few microns thick. The team is developing advanced tools and measurement techniques for use in reactors under the extreme conditions necessary to grow these compound semiconductor films. These measurements may permit much more precise control over important physical parameters that establish the electrical and optical properties of products made in these reactors. The team has demonstrated improved process control over critical temperatures at key growth steps. It has also used advanced chromatographic techniques to monitor gas compositions at critical intervals. Using these methods, the quality and uniformity of the films can be improved dramatically.

The researchers are also investigating the use of sophisticated, tiny semiconductor structures (nanoparticles, or "quantum dots") to convert the monochrome emissions characteristics of inorganic compound semiconductor LEDs to more useful broadband emissions that appear white. The team is producing samples to determine their performance attributes. It is also investigating means for incorporating the quantum dots into thin films that can be applied to the LED chips to produce white LED lamps based solely on semiconductors. Devices like these eventually may be made on a commercial scale, providing an important step forward in DOE's quest of vastly increased efficiency in LEDs.

Nanostructured High Performance Ultraviolet and Blue LEDs

Investigating Organization

Brown University

Principal Investigator

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Subcontractor

None

Funding Source

Building Technology/NETL

Award

DOE share: \$900,000; applicant share: \$229,033

Contract Period

October 2003 to October 2006

Research Topic

Topical Area 1: Applied Research Area

Task 1.1: Inorganic Materials Research

Subtask 1.1.2: High Efficiency Visible and Ultraviolet Semiconductor Materials for LED-Based General Illumination Technology

Brown University's work is oriented toward creating a light source that has a longer lifespan, uses less energy, and is about three times more efficient than standard fluorescent lights in office buildings. By improving silicon wafers or media that produce light, the project integrates nanostructured active materials into synthetically grown crystals to increase light emissions. The project also combines novel optical, chemical, and physical methods to enhance photons, which increase efficiency.

In this project, nanomaterial science is synergized with fundamental optical physics concepts pertaining to light-matter interaction. The goal is to develop a new class of high-performance light emitting diodes in the blue and near ultraviolet for solid state lighting applications, covering the spectral regime of approximately 370-480 nm. The overall mission is to implement novel, highly adaptable device concepts that enable flexible use, and match the broad spectrum of requirements posed by contemporary solid state lighting approaches. The light emitters will be based on nanostructured gallium nitride and related semiconductors, which are encased by engineered nano-optical photonic confinement structures. The researchers aim to reach the goal of a highly wall-plug-efficient, high-power optical device (> 100 lm/W) by concentrating on two specific, highly interrelated elements within the LED.

First, a nanostructured active media will be created to enhance the internal radiative efficiency by using advanced concepts in epitaxial growth for synthesizing quantum dots and quantum

wires. The design principles involve the enhancement of the radiative cross section, acquired from microscopic principles, by the combined interplay of electronic confinement, strain, and piezoelectric polarization fields. The researchers' goal is to reach unity internal efficiency in the active medium. Furthermore, the nanostructured media will provide a designated electronic environment that will maximize the capture of electrically injected carriers into the quantum confined radiative centers.

Second, the research will focus on the design and fabrication of advanced subwavelength optical confinement structures. These structures will encase the nanostructured active medium for enhancing the spontaneous and stimulated emission by enhancing light-matter interaction at a fundamental level and for efficiently extracting and distributing the photons for delivery into specific geometrical radiation patterns by design.

The nano-optical resonator concepts use recent work by the principal investigators with planar resonant cavity LEDs to develop efficient mesoscopic optical confinement structures in three dimensions. Such mesoscopic optical concepts merge optical near field physics with subwavelength diffractive elements. These devices exploit a large index of refraction contrasts that are provided by new approaches to microcavity fabrication in the GaN/AlN system, while providing electrical access with heterostructure engineering concepts, such as those based on tunnel junctions.

Novel Approaches to High-Efficiency III-V Nitride Heterostructure Emitters for Next-Generation Lighting Applications

Investigating Organization

Georgia Tech Research Corporation

Principal Investigator

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Subcontractor

None

Funding Source

Building Technology/NETL

Award

DOE share: \$428,799; applicant share: \$130,346

Contract Period

October 2003 to October 2006

Research Topic

Topical Area 1: Applied Research Area

Task 1.1: Inorganic Materials Research, Subtask 1.1.2

Subtask 1.1.2: High Efficiency Visible and Ultraviolet Semiconductor Materials for LED-Based General Illumination Technology

Georgia Tech Research Corporation is working to produce new knowledge of the roles various materials have on LED properties and efficiencies and a more detailed understanding of the fundamental chemical process behind light production. The University's goal is to assimilate new information that enables the possibility of developing more efficient green LEDs that could, in turn, produce a new LED device capable of complete color-spectrum white light.

The Georgia Tech research program will develop technologies for the growth and fabrication of high-quality green light-emitting devices in the wide-bandgap III-V nitride InAlGa_N materials system. The group's research will include four components. Part One will make use of advanced equipment for the metal organic chemical vapor deposition (MOCVD) growth of III-nitride films and the characterization of these materials. Part Two focuses on the development of innovative growth technologies for high-quality green light-emitting diodes. Part Three will involve the study of strain effects and piezoelectric and polarization effects upon the LED performance. Part Four will focus on the design, fabrication, and testing of nitride LEDs.

Phosphor-Free Solid State Light Sources

Investigating Organization

Cermet Inc.

Principal Investigator

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Subcontractor

Georgia Tech

Funding Source

Building Technology/NETL

Award

DOE share: \$3.7 million; applicant share: \$926,352

Contract Period

October 2003 to October 2006

Research Topic

Area 1: Applied Research Area

Task 1.1: Inorganic Materials Research

Subtask 1.1.1: Novel Substrates, Buffer Layers and Wafer Engineering for Efficient Optical Light Extraction and Thermal Management

Cermet's work focuses on growing conventional materials on novel substrates that possess unique physical properties with less internal strain. This process has the potential to increase efficiency; have emissions that can be adjusted by carefully applying potentials across the substrate; and can be made to behave like a phosphor, absorbing photons of one color and emitting new ones that are of a different color

The goal of Cermet's effort is to implement large-area zinc oxide fluorescent substrate technology and state-of-the-art, lattice-matched nitride epitaxy technology to address substrate, epitaxy, and device limitations in the high growth area of solid state lighting. Cermet, in collaboration with researchers at Georgia Institute of Technology, will bring several technological innovations to the marketplace, including the following:

1. *Truly lattice matched, low defect density (as low as 10^4 cm^{-2}) nitride emitter structures resulting in significantly reduced non-radiative recombination centers.* This goal will be achieved by combining molecular beam epitaxy (MBE) and metallorganic chemical vapor deposition (MOCVD) with a ZnO substrate that is lattice matched to nitride LEDs in the wavelength range of 330 to 420 nm. Shorter wavelength designs are also possible using strain compensated layer growth.

2. *White light emission via a self-fluorescing mechanism in the ZnO substrate.* This will be accomplished by doping the ZnO substrates to yield emission in the vision spectrum. Optical pumping of the substrate will be achieved with the integrated nitride emitter.
3. *Ability to adjust the color content of the white light.* This will be achieved by adjusting the doping concentration of the substrate.

Development of Photonic-Crystal LEDs for Solid State Lighting

Investigating Organization

Sandia National Laboratory

Principal Investigator

Robert M. Biefeld, (505) 844-1556

Subcontractors

NA

Funding Source

EE Science Initiative

Award

\$500,000

Contract Period

October 1, 2003 to September 30, 2005

Research Topic

Topical Area 1: Applied Research Area

Task 1.1: Inorganic Materials Research

Subtask 1.1.2: High Efficiency Visible and Ultraviolet Semiconductor Materials For LED-Based General Illumination Technology

SNL will develop photonic lattices for improving the efficiency of blue LEDs based on Indium Gallium Nitride (InGaN) emissive layers. The overall goal of the project is to double the external quantum efficiency on InGaN LEDs. The researchers are working on improving the efficiency, directionality and flux of LEDs in the visible spectral range.

The project will include detailed theoretical calculations to design photonic lattices, process development to fabricate the necessary nano-scale features, characterization of photonic lattices to confirm theoretical calculations and provide design guidelines, and fabrication of optimized lattices. The photonic lattice, which is a 2-dimensional photonic crystal, can improve the efficiency through two different mechanisms- improvement of the radiative efficiency and improvement of the extraction efficiency. Extensive process development will be performed to fabricate the extremely fine nano-scale features. Characterization of photonic lattices with emissive layers will be performed on the wafer in order to confirm theoretical calculations and provide design guidelines. Finally, complete LEDs will be fabricated using the optimized photonic lattices.

Development of UV-LED Phosphor Coatings for High Efficiency Solid State Lighting

Investigating Organization

University of Georgia Research Foundation

Principal Investigator

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Subcontractors

GE Global Research

Funding Source

EE Science Initiative

Award

\$418,068

Contract Period

October 1, 2003 to September 30, 2005

Research Topic

Topical Area 1: Applied Research Area

Task 1.2: Advanced Inorganic Devices Architectures & Conversion Materials

Subtask 1.2.2: High Temperature, Efficient, Long-Life Phosphors and Encapsulants for Wavelength-Conversion and Packaging

The objective of the work is to develop highly efficient solid state lighting sources based on UV-LED + phosphor combinations. Their methods are focused on improving the phosphor coating conversion efficiency in UV-LEDs, where the fundamental quenching mechanisms for phosphor coatings will be determined and quantified.

To increase the efficacy of white light devices, new phosphors for UV-LED excitation have been developed at GE during the last 6 years. However, the extreme conditions (compared to standard fluorescent lamps) in UV-LED-based devices, such as elevated temperatures and incident light intensities, can lead to luminescence losses. The goal of the program is to find the origin of the losses and quantify the loss parameters in terms of quenching temperature, ionization threshold, and saturation flux. These parameters will then be used to establish design rules for the solid state devices that will operate within a parameter space that is defined by high efficacy, good color rendering, and high lumen maintenance.

In addition to standard emission and photoexcitation measurements, the efficacy of the material is being studied as a function of temperature. These studies will be complemented by time-resolved measurements using pulsed LEDs or laser sources with nsec resolution, and will lead to a determination of the quenching temperature. In order to identify the quenching mechanism, a unique method called thermally stimulated luminescence excitation spectroscopy will be used.

This method has been developed for the characterization of phosphor materials. To study saturation processes, the phosphor materials are exposed to high intensity laser radiation. Finally, blends of phosphors will be studied to monitor and evaluate the importance of energy transfer and migration within the phosphor blend.

The set of relevant parameters established during the experiments will then be used to establish design rules. This information will aid designers in developing LED packages that will minimize or even eliminate many of the phosphor quenching pathways. These rules will allow for optimization of the phosphor composition and the geometry of the LED-phosphor combination with respect to the LED emission characteristics. Thus, the LED package can be readily adapted to take full and immediate advantage of the rapidly advancing UV-LED technology.

Innovative Development of Next-Generation and Energy-Efficient Solid State Light Sources for General Illumination

Investigating Organization

George Tech Research Corporation

Principal Investigator

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Subcontractors

Funding Source

EE Science Initiative

Award

\$625,000

Contract Period

October 1, 2003 to September 30, 2005

Research Topic

Topical Area 1: Applied Research Area

Task 1.1: Inorganic Materials Research

Subtask 1.1.1: Novel Substrates, Buffer Layers and Wafer Engineering for Efficient Optical
Light Extraction and Thermal Management

This project will focus on two main areas 1) the development of lattice-matched emitters on native and non-native III-Nitride substrates materials and 2) the implementation of Next Generation Solid-State Emitters.

Development of lattice-matched emitters on native and non-native III-Nitride substrates:

Numerous substrate technologies offer the possibility of lattice-matched growth to alloys of GaN. These include AlGaIn on Lithium Gallate (~330 nm) and GaInN on Zinc Oxide (~415 nm), but these have had limited use for III-Nitrides emitters due to temperature and processing difficulties that still need to be addressed. Other possible alternative substrate technologies shall be identified and investigated in this work. Another approach to obtaining low defect GaN templates shall be the removal of the ZnO, LGO, or other substrates (such as Silicon) at growth temperature. Removal of the substrate will help to minimize the defects (and strain) generated in the epilayer during cool down due to the difference in the CTE at growth temperature. Silicon will be preferred for this process because of the lower production cost.

Next generation solid-state emitters: In this work, phosphors that are capable of efficient pumping at 370-400nm shall be developed to allow the development of trichromatic type lighting sources similar to fluorescents. III-Nitride emitter structures shall also be developed that will enable multiple wavelength emission from the same device. This shall be achieved by either using light emitting diodes containing multiple quantum wells to yield different emission

wavelengths, or using separately controllable devices coupled together using tunnel junctions. Such devices will allow multiple pump wavelengths to more efficiently pump the different phosphors. Another innovation shall be the use of vertical cavity and other structures for improved phosphor coupling to yield higher light extraction from the front of the device to remove the halo effect.

Novel LED Phosphor Research

Investigating Organization

University of California-San Diego

Principal Investigator

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Funding Source

EE Science Initiative

Award

\$439,814

Contract Period

September 2001 to November 2002

Research Topic

Topical Area 1: Applied Research Area

Task 1.2: Advanced Inorganic Device Architectures & Conversion Materials

Subtask 1.2.2: High Temperature, Efficient, Long-Life Phosphors and Encapsulants for
Wavelength-Conversion and Packaging

There are two possible structures for a white LED. The first option is to develop an efficient white-emitting material that can replace the red-, green- and blue-emitting materials in the classic LED heterostructure.

The second option is to embed a single composition, white-emitting material or three-phosphor blend (red, green, and blue) into the epoxy dome that surrounds the UV-emitting LED heterostructure. Existing white LEDs use a blue-emitting diode that excites a yellow-emitting phosphor embedded in the epoxy dome. The combination of blue and yellow makes a white-emitting LED.

The University of California-San Diego has discovered and developed a single composition white-emitting phosphor that is a terbium activated and cerium co-activated oxide. Cerium efficiently transfers energy to terbium, which mainly has a green emission with blue and red satellite peaks. Cerium-activated oxides have a saturated blue emission, but a long emission tail that extends into the green and red regions of the visual spectra. By enhancing the green and red emission from this phosphor using terbium, an efficient, long UV-excited white-emitting phosphor may be achieved. In addition, a tri-blend phosphor mixture has been discovered.

Novel LED Structures

Investigating Organization

University of California-Santa Barbara

Principal Investigator

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Subcontractors

Lighting Research Center

Funding Source

EE Science Initiative

Award

\$2,995,155

Contract Period

September 2001 to September 2004

Research Topic

Topical Area 1: Applied Research Area

Task 1.1: Inorganic Materials Research

Subtask 1.1.3: Reliability and Defect Materials Physics for Improved LED Lifetime

Researchers at the University of California-Santa Barbara are working to develop a solid state light source with improved power efficiency and luminous efficiency. Led by Dr. Shuji Nakamura, the project team is exploring the fundamental issues associated with nitride-based solid state lighting.

The work at the Solid State Lighting and Display Center at the University of California-Santa Barbara focuses on vertical cavity emitting structures, while the work at the Lighting Research Center at Rensselaer Polytechnic Institute focuses on challenges in packaging, testing, and evaluation of nitride-based solid state lighting. Recently, the group has achieved resonant cavity RC-LEDs showing strong amplified spontaneous emission in the blue spectral region. The RC-LEDs incorporate mirrors with reflectivities as high as 96% to boost the light extraction efficiency. A new, highly conductive p-metal mirror was developed, and modeling predicts that the efficiency of these new structures should exceed 50%. White solid state emitters have also been achieved by combining the blue LEDs with red and green phosphors to make white. The green phosphors had conversion efficiencies of 74%. More work is needed on the red phosphors, which currently exhibit only 24% conversion.

Development of Silicon Nanocrystals as High Efficiency White Phosphors

Investigating Organization

InnovaLight

Principal Investigator

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Funding Source

Small Business Innovation R&D, Phase 1

Award

\$100,000

Contract Period

July 2003 to April 2004

Research Topic

Topical Area 1: Applied Research Area

Task 1.2: Advanced Inorganic Device Architectures & Conversion Materials

Subtask 1.2.1: Advanced Architectures for High-Power-Conversion Efficiency Emitters

Silicon nanocrystals produced and capped in the sub-10nm regime are efficient light emitters in the visible range due to quantum confinement effects. The specific color of emission is dictated by the size of the particle. An ordered distribution of colors produces white. This characteristic, coupled with nanocrystalline silicon's inherent stability and efficiency, makes these materials appropriate for use as phosphors with blue or near-UV high brightness light emitting diodes (HB-LEDs) in producing efficient white light for the general illumination market— a large and compelling market opportunity.

Silicon holds great promise in this application. First, silicon is capable of high efficiencies. Researchers have shown efficiencies approaching 90% from photo-excited silicon nanoparticles prior to any attempt to optimize emission. Second, the inherent stability of silicon, firmly substantiated over its 30 years as the fabric of modern day electronics, uniquely enables long lifetimes. Color stability is also achieved using a single material solution to reach all of the colors of the visible spectrum. This avoids the differential aging characteristic of other approaches requiring multiple material compounds to do the same thing. Third, these novel materials can be tuned to achieve a high quality white light by simply controlling the size distribution. Lastly, the surface passivations of the particles enable them to be suspended in a variety of solutions that in turn enable a number of efficient and well-understood, solution-based deposition schemes, such as ink jet printing. This is an important issue for manufacturability, and for successful commercialization. The combination of these advantages makes silicon a compelling option for HB-LED phosphors for white light emission.

InnovaLight has already produced unique size-controlled silicon nanocrystals in a variety of colors (color being a function of size). These materials have demonstrated high initial

efficiencies. During the course of this grant, improvements to the photoluminescent quantum efficiency and color tunability will be achieved through synthetic process control, particularly in the area of surface passivation. In addition, nanocrystal size control and distribution will be optimized to yield the highest quality white light.

Efficient Hybrid Phosphors for Blue Solid State LEDs

Investigating Organization

PhosphorTech Corporation

Principal Investigator

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Funding Source

Small Business Innovation R&D, Phase 1

Award

\$99,984

Contract Period

July 2003 to April 2004

Research Topic

Topical Area 1: Applied Research Area

Task 1.2: Advanced Inorganic Device Architectures & Conversion Materials

Subtask 1.2.2: High Temperature, Efficient, Long-Life Phosphors and Encapsulants for Wavelength-Conversion and Packaging

PhosphorTech is pursuing the development of high performance fluorescent materials for next generation lighting application using solid state lamps. The novel phosphor materials and lighting devices will be based on hybrid organic/inorganic systems with superior color rendering and power conversion efficiencies to the current state of the art. These materials will be fabricated using controlled synthesis techniques. Existing UV-efficient silicate phosphors will be modified to allow blue light absorption and broadband emission in the yellow-green. The goal of Phase I is a white LED having a luminous efficiency of 30 lm/W (2 times that of incandescent bulbs) and a color rendering index over 80. The goal of Phase II is a white LED having a luminous efficiency > 50 lm/W and a CRI > 90.

The availability of efficient white LEDs will open up a number of exciting new application markets, such as white light sources replacing traditional incandescent and fluorescent light bulbs and efficient low-voltage backlights for portable electronics. The down-converting hybrid phosphor materials could also be used to make pixelated screens for full-color photonically driven displays (using RGB filters), and even in maintenance-free LED-based traffic lights.

Enhanced Optical Efficiency Package Incorporating Nanotechnology based Downconverter and High Refractive Index Encapsulant for AlInGaN High Flux White LED Lamp with High Luminous Efficiency LED Phosphor Performance (Phase 1)

Investigating Organization

Nanocrystals Technology

Principal Investigator

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Funding Source

Small Business Innovation R&D, Phase 1

Award

\$99,933

Contract Period

July 21, 2003 to April 20, 2004

Research Topic

Topical Area 1: Applied Research Area

Task 1.2: Advanced inorganic Device Architectures & Conversion Materials

Subtask 1.2.2: High Temperature, Efficient, Long-Life Phosphors and Encapsulants for Wavelength-Conversion and Packaging

Nanocrystals Technology (NCT) is working to develop unique nanophosphors in the size-range of 2 to 10 nm. This project uses a new class of downconverter nanophosphors to more efficiently absorb UV/blue light and simultaneously downconvert to white light. The nanophosphor efficiency compares well with best commercially available YAG:Ce bulk phosphors, which are currently used to generate white light LEDs from blue LEDs. Due to elimination of light-scattering, the researcher anticipates a significant enhancement of the luminous efficacy of high brightness LED-based white lamps for general illumination applications. When used with bulk YAG:Ce phosphor, NCT's high refractive index (HRI) nanocomposites have yielded enhancement of > 20% in luminous efficacy (at the chromaticity coordinates) compared to conventional encapsulant when coupled to a blue LED lamp. Appropriate surface modification will be developed for each of the nanophosphors to disperse into silicone-based matrices without agglomeration to achieve high optical transparency in the visible-spectral region. When fully optimized, the high refractive-index nanocomposites and nanophosphors are expected to increase white light emission by 100%, bringing the luminous efficacy of white light to 75 lm/W using a cost-effective packaging technology. Combining different nanophosphors will achieve varying color temperatures.

Gallium Nitride Substrates for Improved Solid State Lighting

Investigating Organization

Kyma Technologies

Subcontractors

Georgia Institute of Technology

Principal Investigator

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Funding Source

Small Business Innovation R&D, Phase 1

Award

\$100,000

Contract Period

July 2003 to April 2004

Research Topic

Topical Area 1: Applied Research Area

Task 1.1: Inorganic Materials Research

Subtask 1.1.1: Novel Substrates, Buffer Layers and Wafer Engineering for Efficient Optical Light Extraction and Thermal Management

Device cost and limitations in GaN materials technology, manifested by the lack of a large, native-nitride substrate, currently holds back the incorporation of GaN-based devices into solid state light sources. The use of GaN substrates will address these issues by reducing the number of performance-hindering defects in devices and by achieving lower costs because of fabricating devices with higher yields. Kyma Technologies has developed a process for fabricating 50 mm GaN substrates, enabling the realization of high-efficiency blue-green and UV LEDs.

The availability of freestanding GaN substrates should significantly simplify the growth of GaN since lattice and thermal issues will no longer be relevant. Homoepitaxy growth decreases the average GaN threading dislocation density, thus improving the electrical properties of the material. The accomplishment of low-dislocation-density GaN material will increase lifetime and brightness in optoelectronic devices. Moreover, lower defect levels should also increase thermal conductivity of the GaN, which will be beneficial for device operation. Wafer cracking and/or bowing will be minimized because the coefficient of thermal expansion between the GaN epitaxial layer and the substrate will be the same.

Kyma Technologies and Georgia Tech are developing a process for production of LED device structures with low defect densities on gallium nitride substrates. The nitride MOVPE growth process is being used to grow gallium nitride epitaxial layers on this substrate material. The program will determine the optimal growth conditions for MOCVD growth of GaN on GaN

substrates. The GaN substrate has structural and thermal properties that will improve gallium nitride and AlGaN layers in the device structure. The electrical and optical characteristics and defect density of GaN epitaxial layers on GaN substrates will also be characterized.

Kyma Technologies has already demonstrated the fabrication of blue LEDs on gallium nitride substrates. The initial results are very promising with a forward voltage (V_f) of 3.0 – 3.5 V at 20 mA for a LED emitting at a wavelength of 450 nm.

Novel Low-Cost Technology for Solid State Lighting

Investigating Organization

Technologies and Devices International

Principal Investigator

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Funding Source

Small Business Innovation R&D, Phase 1

Award

\$99,976

Contract Period

July 2003 to April 2004

Research Topic

Topical Area 1: Applied Research Area

Task 1.1: Inorganic Materials Research

Subtask 1.1.1: Novel Substrates, Buffer Layers and Wafer Engineering for Efficient Optical Light Extraction and Thermal Management

The work of Technologies and Devices International focuses on demonstrating a novel epitaxial technology with substantially reduced process cost for fabrication group-III nitride epitaxial structures for white light emitting diodes. The technology is based on hydride vapor phase epitaxy (HVPE) of AlGaIn/GaN light emitting structures.

For group-III nitride semiconductors, HVPE is known to be a low-cost method for fabrication of thick quasi-bulk GaN materials, GaN-on-sapphire, and AlN-on-sapphire templates used as substrates for device fabrication. The Phase I objective is to extend HVPE cost-effective epitaxial technology for the fabrication of white light emitting devices. Al(In)GaIn-based blue ultra violet emitters fabricated by HVPE technology for lighting applications will be demonstrated.

This technology will also provide a number of technological advantages for the growth of high-efficient blue and UV light-emitting structures. General lighting devices will be fabricated by packaging the blue or UV LEDs with a white light conversion phosphor blend. Potential applications include residential general illumination, aviation, and hazard indicators.

The researchers have also designed light emitting structures and investigated material deposition HVPE technology. A novel HVPE method has grown two sets of epitaxial materials. Grown samples are under characterization. The next step will be to grow p-type AlGaIn layers, and to fabricate structures for blue-UV LED dies processing and delivery of pn structures for phosphorous deposition.

Ultraviolet LEDs for Solid State Lighting

Investigating Organization

Cermet, Inc.

Principal Investigator

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Subcontractors

None

Funding Source

Small Business Innovation R&D, Phase 1

Award

\$99,694

Contract Period

July 2003 to April 2004

Research Topic

Topical Area 1: Applied Research Area

Task 1.1: Inorganic Materials Research

Subtask 1.1.2: High Efficiency Visible and Ultraviolet Semiconductor Materials For LED-Based General Illumination Technology

Two approaches are emerging as viable techniques for the production of solid state white light: visible wavelength LEDs coupled with modified phosphor compositions and UV emitters coupled with traditional, highly efficient YAG phosphors. The latter approach has the advantage of producing light with familiar color temperatures (warmth), which will greatly enhance the adoption rate of the light source by the public. However, UV (340 nm and 280 nm) semiconductor emitters with sufficient power required to stimulate YAG phosphors are not available. Under a DOE SBIR award, Cermet and Georgia Institute of Technology will address this technology by developing state-of-the-art UV emitter structures.

The goal of this program is to develop the technology necessary to enable commercial production of high-quality (In,Al,Ga)N epitaxial materials and high-performance UV LEDs for solid state lighting applications on AlN substrates. This will be accomplished by addressing three major areas:

- Development of production grade bulk AlN wafers using Cermet's Vapor Growth Process
- Development of better quality materials, which include p- and n-type doped AlGaIn and InAlGaIn-based multi-quantum wells
- Introduction of novel LED device structures

The team's approach will address three major technological barriers in the development of UV emitters:

- Development of high-quality, bulk AlN crystals to eliminate dislocations, which can be a major contributor to efficiency roll-off at high drive current densities. Bulk AlN minimizes thermal expansion cracking in high Al-content emitters. Aluminum nitride substrates are transparent in the UV portion of the spectrum, allowing through-wafer emitter designs into the deep UV. Lastly, AlN has a significant thermal conductivity, enabling effective power management of large area power (>0.5 watt) LEDs for SSL needs.
- Development of high **n**-type doping level in $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys
- Development of high **p**-type doping level in $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys

OLED Durability and Performance

Investigating Organization

General Electric Global Research

Principal Investigator

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Subcontractors

Cambridge Display Technologies

Funding Source

Building Technology/NETL

Award

\$2,951,064

Contract Period

September 2000 to November 2003

Research Topic

Topical Area 1: Applied Research Area

Task 1.7: Organic Technology Integration

Subtask 1.7.1: High-Flux, Reliable Packages for Large-Area Incandescent and Fluorescent Building Block Technologies

GE Global Research is conducting a three-year program to reduce the long-term technical risks that are keeping the lighting industry from embracing and developing OLEDs. The specific goal is a demonstration light panel that delivers white light with brightness and light quality comparable to a fluorescent source and with an efficacy better than that of an incandescent source. This will require significant advances in three areas: (a) improvement in OLED energy efficiency at high brightness; (b) improvement of white light quality for illumination; and (c) the development of cost-effective, large-area fabrication techniques.

The project's key progress so far has been to demonstrate that high illumination-quality white light could be generated using OLED technology; and to develop a new, fault-tolerant device architecture that should enable low-cost, large-area OLEDs for illumination. The effort is divided into three main technical phases and is designed to achieve a significant milestone at the end of each year.

In Phase I, GE developed a small area-efficient white light device. This task involved sourcing available blue polymers and using these to fabricate and evaluate device performance. One polymer was chosen for white device development. In parallel, new polymers and device designs are being investigated for increased efficiency over the course of the program.

Phase II focused on scaling up the white device manufacture to a device measuring 36 square inches. Small-scale device fabrication was also pursued to validate critical process changes efficiently, and to develop a process compatible with newer, more efficient devices as they become available.

Phase III, ongoing in 2003, includes developing the technology and system optimization required to build a 2 ft. x 2 ft. demonstration panel for white-light illumination.

Polymer OLED White Light Development Program

Investigating Organization

OSRAM Opto Semiconductors

Principal Investigator

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Subcontractor

None

Funding Source

Building Technology/NETL

Award

DOE share: \$4.65 million; applicant share: \$4.65 million

Contract Period

October 2003 to October 2006

Research Topic

Topical Area 1: Applied Research Area

Task 1.7: Organic Technology Integration

Subtask 1.7.1: High-Flux, Reliable Packages for Large Area Incandescent and Fluorescents

Building Block Technologies

OSRAM-OS is working to develop, fabricate, and fully characterize a 12-inch square OLED white light prototype for DOE. The work is being conducted at the company's polymer OLED materials and device development center in San Jose, CA. OSRAM-OS works closely with major suppliers of electro-active polymer materials for OLEDs. The Product Development Group in San Jose manages module (luminaires design and electronic control) design work. The company's group at the OSRAM/Sylvania Central Research Center in Danvers, MA manages lighting measurements.

The advanced white light prototype will be based on use of multiple discrete 3-inch square white light devices fabricated on glass substrates. Two approaches for achieving white light from the discrete devices will be pursued in parallel. In the first, a broadband light-emitting co-polymer will be used for the generation of white light, from either a single large area emitting film, or from a relatively small number of segmented emitting films. In the second approach, a larger array of color tri-stripes, or tri-segments, of red, green, and blue polymer emitters combined with a light diffuser will be used to produce a white light. In both cases, the use of molecularly dispersed triplet emitters will be investigated to improve efficiencies. Alternatively, and through work with materials suppliers, polymer materials that incorporate triplet emitters in the polymer backbone will be used.

In the third year of the program, OSRAM-OS expects to produce a color-balanced 12-inch square OLED white light with luminous efficacy of 20 lm/W at 800 cd/m², and achieve an operating life of 3,000 hours (to half luminance).

General Illumination Using Dye-Doped Polymer LEDs

Investigating Organization

Intelligent Optical Systems

Principal Investigator

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Funding Source

Small Business Innovation R&D, Phase 1

Award

\$99,998

Contract Period

July 2002 to June 2003

Research Topic

Topical Area 1: Applied Research Area

Task 1.5: Organic Materials Research

Subtask 1.5.1: High Efficiency, Stable Organic Emitter Materials For
OLED-Based General Illumination Technology

New illumination technologies should be cost effective and have an acceptable color-rendering index (CRI). OLEDs as broadband white light sources are one such technology. A major advancement in the development of OLEDs has been the implementation of phosphorescent dyes as the emitting species, which has prompted large device enhancements to both monochrome and broadband OLED systems.

These advances have also created opportunities to enhance lighting efficiency by mating electrophosphorescence with novel polymers. Intelligent Optical Systems (IOS) is pursuing this pathway, which is expected to result in easy-to-process polymer materials. These materials have exceptional properties, and are an inexpensive and efficient general illumination lighting source. This methodology will allow polymer light emitting devices (PLEDs) to obtain the outstanding efficiencies of small molecule-based devices.

IOS has successfully demonstrated a white light source for general illumination that uses the triplet emission from one or more dyes embedded in a novel polymer matrix. Using this approach, the devices maximize the conversion of charge-to-light. The methodology is unique because the polymer matrix allows the use of highly efficient phosphorescent dyes as emitters within the device architecture. The researchers expect that external device efficiencies will be greater than 4%, while maintaining excellent color rendering quality and high brightness.

In the first phase of the project, IOS demonstrated the feasibility of producing PLEDs significantly more efficient than existing fluorescent-based white devices. Future research will involve strengthening and enhancing the PLED technology by studying performance degradation

issues. Material purity, device fabrication pathways, and device structural design will be researched. This research will be instrumental in improving the device fabrication capabilities, material analysis, and overall lighting knowledge needed for this technology to improve solid state lighting efficiency.

New Solid State Lighting Materials (Phase 1)

Investigating Organization

Maxdem

Principal Investigator

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Funding Source

Small Business Innovation R&D, Phase 1

Award

\$99,957

Contract Period

July 2002 to June 2003

Research Topic

Topical Area 1: Applied Research Area

Task 1.5: Organic Materials Research

Subtask 1.5.1: High Efficiency, Stable Organic Emitter Materials For
OLED-Based General Illumination Technology

In Phase 1, Maxdem developed highly efficient red and green phosphorescent polymers and fabricated electroluminescent devices. A structural concept that controls the energy flow within the emitting layer was devised that allows mixing of different color phosphors without energy transfer. The potential of this concept to generate white light from a single-layer polymeric LED was verified. Applications of this technology may be either for commercial or military purposes such as displays, lasers, sensors, or photovoltaic devices.

New Solid State Lighting Materials (Phase 2)

Investigating Organization

Maxdem

Principal Investigator

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Funding Source

Small Business Innovation R&D, Phase 2

Award

\$749,813

Contract Period

June 2003 to June 2005

Research Topic

Topical Area 1: Applied Research Area

Task 1.5: Organic Materials Research

Subtask 1.5.1: High Efficiency, Stable Organic Emitter Materials For OLED-Based General Illumination Technology

Maxdem is currently working to extend Phase I results to a three-color system. In addition, more economically efficient methods of synthesis of the new phosphors are being developed. In the first quarter of Phase II, new monomers and phosphors have been prepared. These will be tested in OLEDs when all three (blue, green, red) phosphors have been fully characterized.

Maxdem will work to develop white-emitting electroluminescent materials and devices. A concept to control energy flow within the emitting layer will be used to prepare and evaluate a large number of polymers and blends. Optimization of material and device structures will result in phosphors meeting solid state lighting system performance and cost requirements.

The goal is to enable broad lighting applications primarily in the commercial and military sectors. The proposed concepts may also have utility in other photonic applications such as displays, lasers, sensors, and photovoltaic devices.

New Stable Cathode Materials for OLEDs

Investigating Organization

International Technology Exchange

Principal Investigator

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Funding Source

Small Business Innovation R&D, Phase 1

Award

\$99,800

Contract Period

July 2003 to April 2004

Research Topic

Topical Area 1: Applied Research Area

Task 1.5: Organic Materials Research

Subtask 1.5.1: High Efficiency, Stable Organic Emitter Materials For OLED-Based General Illumination Technology

International Technology Exchange (Intex) is working to develop a new class of cathode materials that have low work function and are highly stable. Phase 1 of the process will determine the deposition conditions for producing conducting, low-work-function films. Subsequently, the film will be deposited on OLED devices. Their effectiveness as cathodes will be compared with conventional cathode materials. If successful, application of these materials may improve the manufacturability of OLEDs, increasing their prospects for mass production for general illumination.

Intex has done pioneering research in developing amorphous carbon-based nanocomposite materials that can be made electroactive by complexing with a wide range of elements and compounds. The materials are deposited in a vacuum using plasma-enhanced chemical vapor deposition (PECVD) with the substrate at or near room temperature. The films can be deposited on polymeric and other organic substrates, including the organic materials used to fabricate OLEDs.

The nanocomposite films are dense and can be made pinhole-free at a thickness below 1 μm . They have excellent properties as corrosion protection coatings, meaning these films are effective barriers to water and oxygen. The work function can be varied by complexing with elements with different electronegativities. Specifically, complexing with low-work-function elements will produce a nanocomposite film with a low work function that can function as a cathode in OLEDs. The complexing is done during the growth of the film.

The dual function as cathode and hermetic barrier layer can be provided on flexible substrates. Such films have been deposited on polyimide and polycarbonate substrates. The first nanocomposite cathode films were deposited on silicon substrates and the subsequent OLED

layers are deposited on top of the cathode film. The films incorporated aluminum as the complexing element. During the Phase I project, an advanced reactor design will be implemented that will allow the deposition of such cathode films directly on the organic layers.

Novel Light Extraction Enhancements for OLEDs

Investigating Organization

Universal Display Corporation

Principal Investigator

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Subcontractors

Princeton University

Funding Source

Small Business Innovation R&D, Phase 1

Award

\$100,000

Contract Period

July 2003 to April 2004

Research Topic

Topical Area 1: Applied Research Area

Task 1.5: Organic Materials Research

Subtask 1.5.1: High Efficiency, Stable Organic Emitter Materials For OLED-Based General Illumination Technology

In Phase 1, Universal Display Corporation, a developer of OLED technologies for flat panel displays, lighting and other opto-electronic applications, is working to demonstrate innovative techniques to improve OLED power efficiencies, a critical performance attribute for the general lighting industry. Universal Display and its research partners at Princeton University and the University of Southern California are developing several novel approaches for highly efficient white light using the Company's phosphorescent OLED (PHOLEDTM) technology.

In addition to the use of this highly efficient PHOLED technology, better light extraction techniques are required to achieve the power efficiency targets of the general lighting market. In this program, Universal Display and Princeton University will demonstrate the feasibility of using specialized designs, such as lens arrays, on an OLED device to enhance the amount of generated light that is captured or extracted from the device as useful light.

The specific method being implemented is to attach low-cost polymer microlens arrays fabricated in a simple, rapid-molding process to the OLED glass substrate after it has been produced. The feasibility of transferring this approach to a plastic substrate economically will be demonstrated as well. The potential commercial applications of improved and less costly OLEDs include general illumination, automotive, and wearable electronics.

Novel Lower Voltage OLEDs for High Efficiency Lighting

Investigating Organization

Universal Display Corporation

Principal Investigator

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Subcontractors

Princeton University, University of Southern California

Funding Source

Small Business Innovation R&D, Phase 1

Award

\$100,000

Contract Period

July 2003 to April 2004

Research Topic

Topical Area 1: Applied Research Area

Task 1.5: Organic Materials Research

Subtask 1.5.2: Low Voltage, Organic Materials and Structures for High Current Density and Flux Applications

The team led by Universal Display Corporation with their academic partners at Princeton University and the University of Southern California is focusing on the development of novel, low-voltage phosphorescent light emitting structures that will enable OLEDs with power efficiency >20 lm/W at a brightness of 800 cd/m². The power efficient OLEDs will result from the development of innovative, highly conductive hole and electron transport systems in conjunction with high-efficiency triplet emitters. Triplet emitters contain a heavy metal atom that facilitates the mixing of singlet and triplet states, allowing singlet to triplet energy transfer through intersystem crossing. This leads to highly efficient devices where 100% of the excitons can potentially produce optical emission, in contrast to only approximately 25% in conventional fluorescent devices. The high conductivity hole and electron transport systems will be achieved by selecting p- and n-type dopants along with the appropriate organic buffer layers. The resulting structure will be a p-i-n type device. The team has already identified several candidate material systems and is currently working to improve their stability.

The novel structures will also have potential use in energy-efficient, long-lived, solid state white OLED applications in general illumination, automotive, and wearable electronics. The team is already exploring two approaches for generating white light in a parallel Phase 1 SBIR effort. The first approach is based on a simple striped R-G-B configuration, and the second on using a phosphorescent monomer-excimer emission layer. P-i-n doping can be incorporated into both of these approaches.

Furthermore, the compatibility of OLEDs for use on flexible plastic substrates pioneered by the team opens up the possibility for a new generation of illumination sources that are conformable, rugged, and extremely light weight.

Polymer White Light Emitting Devices

Investigating Organization

Reveo

Principal Investigator

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Funding Source

Small Business Innovation R&D, Phase 1

Award

\$99,800

Contract Period

July 2003 to April 2004

Research Topic

Topical Area 1: Applied Research Area

Task 1.5: Organic Materials Research

Subtask 1.5.1: High Efficiency, Stable Organic Emitter Materials For OLED-Based General Illumination Technology

The goals of Phase 1 are to demonstrate the functionality of Reveo's new material technology for light-emitting electrochemical cells (LECs) with frozen *p-i-n* junctions, and to demonstrate the applicability of the materials to organic electroluminescent devices. Devices fabricated with the new materials will be tested for white light quality, high efficiency, high brightness, low operating voltage, and insensitivity to electrode materials and film thickness. Success developing this material may lead to improved solid-state lighting performance for general illumination.

The feasibility of the frozen junction approach was successfully demonstrated in Reveo's recent research for single color light emitting devices and showed great potential in flat panel color displays.

The characteristics of the frozen junction LECs make it possible to fabricate high efficiency, high power output and long lasting light emitting devices at low cost. Because balanced charge injection in LECs is insensitive to the band gap and ionization potentials of semiconducting polymers, frozen-junction LECs provide an approach to fabricating high quality white lights.

There are three main methods that have been proposed to produce white OLED devices using polymers or organic small molecules. 1) The first one is to dope the single host emissive layer with some laser dyes that emit at different color ranges from the host material or blending two different emissive materials. 2) An alternative one is to use a microcavity structure to get two or three emissions simultaneously from one emissive layer. 3) The third one is to use a multi-layered device structure to get different color emission at the same time from different emissive layers.

Since LECs utilize single layer organic materials, the first method is the most suitable for LECs to generate white light. In Phase I, organic emitting materials used in white OLEDs will be used in LECs to demonstrate the feasibility of producing white light. In phase II, organic light emitting materials will be specially designed and synthesized for LEC devices to generate high-efficiency, high-power, long-lasting, and low-cost white light.

The simplest solid electrolyte system was chosen in Phase I to prove the concept of Reveo's innovation. Commercially available poly(ethylene oxide), PEO, will be used as the ion transport material. Organic salts will be synthesized bearing vinyl polymerizable functionality. The new electrolyte system and commercially available emitters will be used to fabricate LECs with frozen *p-i-n* junctions. Devices will be made and tested for unipolar light emission, fast response, high brightness, low operating voltage and insensitivity to electrode materials and film thickness.

End uses include a wide range of OEL display and general lighting applications, including both mini-size and wall-size displays, and single-color to full-color OEL displays and light sources. The Phase I work will validate the proposed material design and device fabrication concept. The results of Phase I will provide a solid foundation for a Phase II program in which Reveo will further improve and refine the material design and device fabrication strategy. The result will be high-quality and high-performance LECs.

Striped and Monomer-Excimer Phosphorescent OLED Technology (Phase 1)

White Illumination Sources Using Striped Phosphorescent OLEDs

Investigating Organization

Universal Display Corporation

Principal Investigator

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Subcontractors

Princeton University, University of Southern California

Funding Source

Small Business Innovation R&D, Phase 1

Award

\$100,000

Contract Period

July 2002 to June 2003

Research Topic

Topical Area 1: Applied Research Area
Task 1.7: Organic Technology Integration

Monomer-Excimer Phosphorescent OLEDs for General Lighting

Investigating Organization

Universal Display Corporation

Principal Investigator

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Subcontractors

Princeton University, University of Southern California

Funding Source

Small Business Innovation R&D, Phase 1

Award

\$100,000

Contract Period

July 2002 to June 2003

Research Topic

Topical Area 1: Applied Research Area
Task 1.5: Organic Materials Research,
Subtask 1.5.1: High Efficiency, Stable
Organic Emitter Materials for OLED-Based
General Illumination Technology

Based on its research in phosphorescent OLED (PHOLED™) technology, the project team has demonstrated OLEDs that are up to four times more power efficient than previously thought possible. Under two DOE SBIR awards, Universal Display, Princeton University, and the University of Southern California are pursuing two novel approaches to broadband white light generation based on this highly efficient PHOLED technology.

The first approach is to develop a novel, low-cost, high-efficiency general illumination light source comprised of a series of striped red, green, and blue PHOLEDs. Fabricating a white OLED light source from a series of striped PHOLEDs has the potential to provide a tunable, white lighting source with the requisite performance for CIE and color rendering. So far, the team has demonstrated the feasibility of using this approach for flat-panel displays.